BENNETT

Potential Stresses in Dielectrics

Electrical Engineering

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POTENTIAL STRESSES IN DIELECTRICS

BY

CLAUDIUS EDMUND BENNETT

B. S., University of Nebraska, 1909

THESIS

Submitted in Partial Fulfillment of the Requirements for the

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

CLAUDIUS EDMUND BENNETT

ENTITLED POTENTIAL STRESSES IN DIELECTRICS

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Ernst Berg
In Charge of Major Work

Ernst Berg
Head of Department

Recommendation concurred in:

Morgan Brooks
Ellery B. Paine
J M Bryant

Committee
on
Final Examination

219461

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POTENTIAL STRESSES IN DIELECTRICS.

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POTENTIAL STRESSES IN DIELECTRICS

I. INTRODUCTION.

The enormous development of high potential apparatus that has taken place in the last few years has placed many new and exacting requirements upon the materials of insulation and raised to importance, questions that before were of only scientific interest. this applies especially to oil which is the most important of them all, Indeed it may be said that the insulating properties of this substance makes possible the long distance electric transmission of energy.

Since a thorough understanding of a phenomenon assists in meeting troubles which arise, it is important to know how oil insulates and how breakdown is brought about. There are certain factors which cause static breakdown and which prepare the way for the formation of the arc, making it easier at one time than at another. As these are recognized and their action understood, the design of high potential apparatus will become more certain and economical.

A material of so much importance as oil should also be subjected to the most careful tests. It should be possible to test different samples of oil so as to state definitely that one was, say ten per cent, better than another yet, at present, one cannot be sure of an advantage unless it is much larger than this amount. If this could be done, manufacturers could try out their different methods of preparation of the oil and, by determining accurately which was best, improve the processes of manufacture. Then too, a delicate and certain test would be useful for the detection of moisture.

Turning to the operating side of the work, after the oil

has been tested for moisture and found defective, there is the problem of drying it and keeping it dry so that the transformer may not be endangered. Because of the expense of drying the oil by the present methods, and the imperfect protection that even this affords to the solid insulating material, the possibility of using a chemical drier as a sort of "watch dog" against moisture is particularily alluring.

This paper is an account of experiments expected to aid in the solution of these three problems.

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He wishes to thank especially Dr.E.J.Berg for his encouragement and assistance in a work that has been, at times, very discouraging. He would thank also Dr.C.P.Steinmetz for valuable suggestions.

II. PRINCIPLES INVOLVED.

When a high voltage is impressed upon a liquid dielectric such as oil, it produces a number of secondary effects that become of importance as the point of breakdown is approached. These serve, in a measure, to prepare the way for the arc and are worthy of some study because of their bearing upon practical tests.

ELECTROSTATIC ATTRACTION. One quite noticeable effect is the distortion of the surface near the electrodes, showing that there is a force acting upon the oil and drawing it out of its level. Just as iron, placed in a magnetic field, concentrates the lines of force and so is subjected to a force tending to draw it to the more intense parts of the field, so oil or any other dielectric whose specific inductive capacity is greater than that of the medium in which it is immersed, concentrates the tubes of force and is subjected to a force tending to draw it to the more intense parts of the field. Except at the surface, this static force produces no tendency to motion in a uniform medium, and therefore cannot create currents in oil of uniform quality. Never-the-less violent currents are actually set up in oil when it is under stress and approaching the point of breakdown, indicating the action of some other force. By the use of a transparent insulator such as kerosene, having in it a few tiny particles to betray the direction and velocity of motion, one may observe these currents. While they are very erratic with almost any form of apparatus, there is this one point of uniformity, that the

liquid attains its greatest velocity when leaving a sharp point or edge where the potential gradiant is greatest. The phenomenon closely resembles the electric wind that blows off from points and edges of a conductor charged to a high potential in air and may be explained in the same way. If a molecule strikes a charged conductor, it receives a charge and is repelled with a velocity depending upon the strength of field at that point. Since the field at a point or edge is more intense than at any other place, it is there that the individual molecules attain their greatest velocity and that the currents in a liquid or gas become noticeable.

SECONDARY EFFECTS. With a liquid insulator, there is in addition, a secondary effect that acts to increase the magnitude of these currents and to prepare the way for the formation of the arc. Unless a viscous liquid is newly distilled and has been handled with extreme care, it is likely to contain bubbles of air or other gas so very minute that their escape is impossible under normal conditions because of the extreme slowness with which a small bubble rises. If such a bubble of air were in oil in the electrostatic field, it would be subjected to a force tending to drive it out, since the specific inductive capacity of the air is less than that of the oil and the oil would try to displace the air. In addition, suppose that the specific inductive capacity of the oil is k, then the gas within the bubble would be subjected to an electrostatic stress k times as great as that of the oil surrounding it. Since oil may exist quietly under stresses which would develop intense corona in air, it is certain that

corona would form within the bubble just the same as it forms in a hole in the insulating material of a high tension cable. The formation of corona would act to increase the size of the bubble in two ways, first, the heat developed would expand the gas, and second, the local heating would decrease the surface tension of the oil and so allow the bubble to increase in size to produce a balance between the pressure within and the external pressure plus that due to surface tension. The bubble would thus be growing in size while within the field and even if it were carried in by an oil current, would assist the current since it would do a greater amount of work in leaving the field than was done on it to bring it in. It seems likely too, that there may be chemical breakdown or perhaps vaporization of the oilunder the electrostatic stress but experiments intended to prove this have failed to give positive results.

EVIDENCES OF BUBBLES. The presence of these bubbles in an ordinary sample ofoil that is apparently clear may be shown by microscopic examination. A microscope of ordinary power will reveal bubbles varying in size from those which are almost large enough to be seen by the naked eye, down to those which appear only as points. It seems likely that the bluish luster which new kerosene shows when viewed at right angles to the direction of the light rays, may be due to multitudes of these bubbles so small that they can reflect only the blue light in the same way that the blueof a steam jet is caused by reflection of the light from minute particles of water that have condensed. The kerosene obtained at this laboratory, when first pumped from the storage tank, is milky white due to

bubbles but these rise to the surface in the first hour, leaving the kerosene a lustrous blue. With long standing undisturbed, the blue becomes a little less noticeable than at first, as though it were due to bubbles, some of which escaped. This view is still further strengthened by the fact that the blue is entirely removed by distillation.

EFFECT OF BUBBLES. The influence of bubbles upon electrostatic disturbance may be shown by experiment. If new oil is arranged to remain for some time under an electrostatic stress which is strong but insufficient to cause breakdown, it is violently agitated at first and gives corona but becomes reasonably quiet after a time and forms corona with extreme difficulty. In the same time it becomes dull in appearance partially losing its original bluish luster. If it is violently agitated by passing a current of air through it for a time, it will again be greatly disturbed by electrostatic stress but the effect wears out more quickly than originally as though the bubbles introduced in this way were larger and escaped to the surface more quickly.

It is quite certain that this effect is not due to moisture introduced with the air or to that originally in the oil. To test this, the oil was treated for several days with calcium chloride to dry it without producing any noticeable decrease in the static agitation. Finally, to make certain that there was no moisture present, the pressure above the oil was decreased to less than a millimeter of mercury and maintained till the bubbles ceased coming off, but this gave a similar

negative result.*

IMPORTANCE OF BUBBLES. The importance of these bubbles becomes apparent when one considers the way in which they make the formation of the arc easy and affect test results. If there are a number of them present when the voltage is applied, they will be set in motion, as noted above, and will increase somewhat in size. In addition, it may be shown from electrostatic theory that they will attract one another when in the field, so tending to combine to form a fewer number of larger bubbles. When out of the field, the larger bubbles would escape to the surface quickly, giving the change noted above that the effect of electrostatic stress is to decrease the number of bubbles.

*It would seem as though the reduction of pressure to a millimeter of mercury would allow the bubbles to expand enormously and rise to the surface but this is not the case. Suppose the diameter of the bubble is about the same as a wave length of light, say 2×10^{-5} inches, which is between the G and H lines of the solar spectrum. The surface tension of mineral oil, as calculated from data given in Landoldt and Bornstein's "Tabellen" is 30.2 dynes per centimeter. The surface tension thus causes a pressure of 34.6 pounds per square inch within the bubble making a total pressure of 49.3 pounds per square inch. Making correction for the new pressure due to surface tension, the removal of the atmospheric pressure causes an increase in diameter of the bubble of only twenty per-cent, and so allows it to rise but little faster than before.

If the combined diameter of these bubbles becomes comparable to the electrode distance, a chance alignment of them as they are passing out of the field may decrease considerably the actual distance of oil that needs to be broken down. If the potential to produce breakdown were in any way a function of the actualoil distance to be penetrated, then test would give this quantity as a variable depending upon the chance alignment of the bubbles. The variation that one obtains in measurement of the voltage to produce breakdown over a spark gap in oil is very great and certainly has in it no element of regularity. Nor can regularity and consistancy be obtained by refinements of measurement or care in manipulation. In fact the results of slow careful work may be inferior to rapid tests under commercial conditions, since the longer time that the oil is under stress gives a greater probability of an unusual alignment or scarcity of bubbles.

INCREASE OF STRENGTH AND STATIC SPARKS. Many experimenters have observed and commented upon the fact that the early discharges through oil seem to increase its dielectric strength but there is another phenomenon which throws some light on this that seems to have received less attention. The frequency with which static discharges occur, previous to the arc, decreases also with continued testing until, with oil that has been tested and filtered many times, such static discharges are totally absent. The increase of strength comes, not by the formation of carbon as some have suggested but rather, in spite of it, for a filtering out of the carbon does not decrease the strength. The change is due to the decrease in the

number of static discharges, and possibly sometimes to the the evaporation of moisture. It may be shown experimentally that small bubbles are capable of producing exactly this effect of static discharge without the formation of the arc. A horizontal spark gap was placed with a capillary glass tube under one electrode, and arrangement made for blowing small bubbles from the tube. Then with voltage far below the normal breakdown value for the gap, short sharp sparks would pass as bubbles were released from the tube but it was only occasionally that the arc was able to form. While it was not possible to measure the size of the bubble when it was in the field, yet the distance broken down seemed out of porportion to the size of the bubble. This might happen by producing a local discontinuity in the field and a sort of progressive breakdown. From this artificial case, it seems likely that the static discharges which occur under test conditions are made possible by the minute bubbles detween the electrodes, and that the increase of strength with sucessive breakdowns is due to the decrease in the number of these bubbles and hence the greater net distance of oil to be broken down.

EFFECT OF PRESSURE. A still further proof that the bubbles play an important part in fixing the dielectric strength of oil is furnished by the effect of pressure. Since oil is practically incompressible, an increase of pressure gives no change of molecular arrangement and hence one would not expect it to produce any appreciable change of dielectric strength. Never-the-less, experiment shows that the increase of strength with increase of pressure is very great, a result that is

difficult to explain except by considering that bubbles are an important factor in producing breakdown. If so, the change in size resulting from a change of pressure would alter the distance of oil to be broken down and so would change the dielectric strength. Since an increase of pressure would decrease the size of the bubbles, it would cause the oil to break down at a higher voltage as is indeed the case.

TRANSIENT VOLTAGES. The experiments of Hayden and Steinmetz* on the disruptive strength of oil with transient voltages seem to point in the same direction and fit in well with this theory. These men have shown that oil has a fairly large "time lag of discharge", and that the voltage necessary to produce breakdown is much larger if transient than if applied for an appreciable time. The authors seem to suggest some rearrangement within the oil or even the influence of bubbles for they say, "When approaching disruptive voltage, mechanical motions of the oil and, occasionally the production of gas bubbles was observed, and also a noticeable time lag, so that three to five seconds had to be allowed at every voltage point before raising the voltage: otherwise the disruption voltage could be considerably exceeded. It seems that electrostatic disruption in oil is a very complex phenomenon involving mechanical motions and chemical dissociations." This lag is exactly the effect which would be produced by bubbles since a very appreciable time would be required for the bubbles to move into alignment, to expand, and to combine to form larger bubbles, and the oil distance to be broken down would be

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*Transactions A.I.E.E. 1909, Page 1125.

much greater in the first instant than later.

INCREASED STRENGTH WITH BLOTTING PAPER. Furthermore, if all motion of the oil is prevented so that the bubbles may not combine or move into alignment, as may be done by using oil impregnated blotting paper, in the apparatus to be described later, the dielectric strength is considerably increased, sometimes nearly trebled. Thinking that this might be due to the insulating properties of the wood fiber, minute holes* were pricked in the blotting paper at various points but discharge did not then occur at a lower voltage or through these holes. This shows that the increased strength is not due to the action of the blotting paper as an additional insulator but must be due to the suppression of motion of the oil.

SUGGESTIONS FOR TESTING OIL. If one may conclude from these various experiments that oil usually contains minute bubbles which affect the breakdown value of the oil and are responsible, in large part, for the variable results of test, then for consistant results, their effect must be eliminated or made to ented all tests in the same amount. One method of accomplishing this result would be to drive the bubbles from the field before they could expand and combine to reach any appreciable size. This has been done in the experiments at this laboratory by directing a steady stream of oil from a centrifugal pump directly across the spark gap. If the

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[*] These holes were made with a carefully sharpened steel wire 0.01 inch in diameter and were perfectly distinct and open after the paper was removed.

bubbles are not allowed to reach appreciable size, the strength of the oil in volts per inch to produce breakdown should be slightly higher under this than under normal conditions. This difference may amount to perhaps 20%[*] increase of strength by circulation (average results, not extreme points). The results with forced circulation were more regular than without, yet the advantage did not seem great enough to make up for the additional complication of the apparatus.

Another method is to prevent the combination and alignment of the bubbles by preventing all circulation of the oil. This may be done by placing it in a porous material whose fibers prevent motion, and has been found quite satisfactory.

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[*] Foersterling and Mann, University of Illinois. Thesis T 1911, Data, Page 32.

III. PRESENT METHODS OF TEST.

The ordinary methods of testing transformer oil are far from satisfactory, since the results are subject to a great deal of variation and do not always indicate the true condition of the oil. Usually the voltage is applied across two small spherical electrodes in a suitable dish, the distance between electrodes being adjusted and measured by a micrometer screw. In one type of apparatus, the electrodes are placed vertically, one above the other, in another style, horizontally. Generally the adjustment is made to a fixed distance and the voltage is increased by small increments to the breakdown value though sometimes the length of the sparkgap is changed while the voltage is maintained constant. To quote from the directions of a prominent manufacturer "The above test should be repeated ten times for each sample.......In case the results of any one of the ten tests varies greatly from the others, it should be checked as it is highly probable that some error has occurred in taking the reading." In other words, any reading that is off value should be rejected and a new one taken. Those who have have made the tests know that such variable results continually occur and that they are not due to errors of reading or adjustment for the trouble lies, not with the observer but with the method of test, for even uniform treatment by skilled observers does not give uniform results.

Fortunately, this method is of value in detecting moisture if it occurs in quantities great enough to seriously weaken the oil but in that case, the results are even more erratic than with oil that iscomparatively dry. One reading may

be very low and the next almost as high as for normal oil. At one time, the conditions may be suchthat many of the minute drops are drawn into the field causing the oil to test lower than it should and then, owing to the disturbance caused by the arc, the drops may be driven away causing the oil to test high in the next few readings. In that case one might reject the low reading if he attempted to repeat it although it would be the one really valuable reading of the set.

While moisture may cause wide variations, yet it is not the only factor that produces error. Oil that is chemically dry and has been filtered to remove solid material gives the same sort of variations for, as has been shown, minute air bubbles may cause error. The variation of the individual readings is so greatthat it is practically useless to compare different brands of oil and the user cannot select a certain sort of oil because of its superior insulating properties. Selection is usually made on the basis of physical characteristics and price.

IV. REQUIREMENTS FOR A TEST.

For a test to be really useful and furnish information in regard to the oil or other dielectric investigated it must, first of all, give accurate results that are reasonably independent of the manipulation and of the conditions that are not easily standardized. While this is the primary requisite for a laboratory method, it alone is not sufficient if the test is to be used under practical conditions. In addition, the method must be simple and require no delicate manipulation or adjustment and should take very little of the operator's time. Also, it is desirable though not absolutely essential that the quantity of the sample taken should be small.*

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* To the criticism which is sometimes made that a test should duplicate as nearly as possible, working conditions it should be noted that this always applies to completed apparatus and very seldom to the material of which the apparatus is constructed. To illustrate, a generator should be tested under running conditions when completed, but the materials of which it is constructed are tested in special forms of apparatus. The permeability meters do not duplicate or even imitate practical conditions, but from the measurements so obtained the proper design is arrived at by calculation. These instruments are used because they afford the most accurate means for comparing different samples.

So it should be with insulating materials. If the

insulating qualities may be determined accurately and surely, by a standard form of test, then it matters very little whether or not this test duplicates closely all the varied conditions to which the material may be subjected in practice.

In any case, the fitness of the material for a given use must finally be found by test of the finished apparatus when the first of a kind is built.

V. TEST APPARATUS.

In the search for a means of testing oil which would be accurate enough to allow careful measurements of dielectric strength and simple enough to be commercially useful in the detection of moisture, many schemes have been tried out at this laboratory.

The first and most obvious thing considered was electrode shapeand terminals of various sizes from needle points to one inch spheres and even segments of spheres of much larger radius were used, and also some "freak" electrodes to produce special forms of fields, but no improvement seems possible in this line. The commercial apparatus as equipped with half inch spherical terminals or discs gives as good results as can be secured by the ordinary methods. Working on another theory, a forced circulation with an oil current directly across the spark gap was introduced. Although this gave somewhat better results than the same apparatus without forced circulation, yet it was scarcely enough to justify the added trouble and complication.

The solution of the problem lies in quite the opposite direction, namely the suppression of all chance currents and the prevention of the escape from the field or the combination of such bubbles as exist in it. This gives an initial condition as uniform as the quality of the oil and excludes outside influences. The circulation of the oil is most easily and effectively prevented by allowing it to soak up and thoroughly impregnate a porous non-conducting material such as pure unsized blotting paper. This is placed between

the electrodes which are submerged in oil to prevent corona and consequent heating and to secure a fairly uniform potential gradiant.

The electrodes which have been found most satisfactory are a plate and a segment of a sphere of large radius. This does not give a field which is uniform or even approximately so, but is one which decreases slowly in intensity from the center outward. Except at the edges, this condition may be expressed mathematically as

$$\frac{d}{dr}\left(\frac{dv}{dx}\right) \text{ is small and nearly constant.}$$

where v is the potential at any point in space between the plates,
x is the curvalinear distance along the tubes of force,
and r is the distance from the center line of the plates.

The sides of the plate should make less than a right angle with the face and the edge should be smooth and sharp. In accord with usual construction, one would round this edge off as a rather open curve, but if this is done, breakdown will almost invariably occur from it instead of from the face of the plate and the results will be erratic. In view of the experiments with various sized electrodes this result is not surprising since a large electrode gives breakdown more easly than one of small curvature. As a paralell case, the rounded edge would allow breakdown more easily than the sharp edge which is really a curve of smaller radius. It does not matter how thin this edge is made so long as it is smooth

and the face of the plate is not changed, and an electrode made as shown in figure 4, as thin as 0.009 inches thick on the edge gave excellent results. This is too frail for ordinary use and the regular electrode has a sharp edge and an an angle of about 60 degrees between surfaces. This is shown in figure 3.

The general form of the apparatus that has been devised for oil testing with the use of blotting paper is shown in figures 2 and 5. It is simple enough that it may be constructed in an ordinary lathe with a minimum of labor and requires no unusual material or drilling of glass. It may be set in on ordinary six inch battery or earthenware jar.

The preparation of the paper is also a simple matter and, for moisture tests, enough may be made up at one time to last for several weeks. Some care must be taken in the selection of the paper as it should be uncolored and free from sizing or foreign material. It should also be of a soft fuzzy grade and soft rolled so that it may fill the space between the electrodes and not fit loosely or too tightly if there is a slight variation in thickness. The paper should be cut into squares little larger than the electrode, say a quarter of an inch and thoroughly dried by gentle heating in an oven.*

*Such an oven may be easily constructed by placing an ordinary 16 or 32 c.p. lamp in a small wooden box, preferably one that has a sliding cover so that the temperature may be controlled by the position of the cover. If desired, a little quicklime may beplaced in the bottom to act as a drier

When dry, the squares are placed in a suitable dish, on edge and separated from one another by pieces of wire, and the dish is then filled very slowly with oil. The advantage of this method of filling is that the oil rises in the paper by capillary action above that outside and so fills the pores of the paper completely, driving the air ahead of it and allowing no bubbles to be imprisoned. After soaking a week, the paper is ready for use.

It may be placed in the apparatus and used directly as a test for this particular sample of oil or it may be put away to be used later with any other oil which is poorer than that with which it is impregnated. If another sample is thought to contain moisture, it should be allowed to filter through the blotting paper and in so doing it will leave its moisture. The paper will thus contain all the moisture that was in the sample of oil and the test may be made as sensitive as desired by increasing the amount of oil passing through the paper. For ordinary work, fifty cubic centimeters is a convenient sized sample. In an hour or so, the oil filters through leaving its moisture in the paper which may then be tested. No attempt should be made to use a paper in less than an hour after filtration starts for the moisture appears first on the surface and must be given time to soak entirely through the paper, otherwise the test values are apt to be too high. This filtration is accomplished by placing the blotting paper on a wire screen in a suitable pan, and pouring the oil into a brass tube which is set on the paper and held in place snugly by a spring.

For precision work, such as a comparison of different

samples of oil or where papers are wanted quickly, they may be prepared in a slightly different manner and will give a little less experimental variation. They should be placed on edge in a dessicator or other dish from which the air may be pumped and the air pressure reduced to a few millimeters of mercury. The papers need not be separated from one another as when working at atmospheric pressure. If the vacuum is low, the moisture will be evaporated in a short time, especially if the whole is gently warmed. The oil should then be admitted and allowed to rise slowly on the paper while still in vacuum. This dries the oil as it enters causing it to boil and foam quite vigorously and insures thit the only moisture in the blotting paper will be that which will be later introduced in suspected samples of oil. In this case, an hour and a half soaking of the paper before itis used is sufficient.

In general, the precautions of the latter method are unnecessary and the former process of preparing the paper is recommended for ordinary use.

VI. MOISTURE IN OIL.

It seems that moisture will gradually accumulate in the oil of a transformer however carefully the case may be sealed. This gradual taking up of water is one of the really serious problems in high potential operation at the present time and protection against it is secured only by continual inspection and expense.

Some companies have a man who regularily visits all the transformers of the system and removes a sample of the oil for inspection. Since the moisture tends to settle, the sample is always taken from the bottom of the case. One method of securing the moist oil is to fasten a dry bottle to a stick, lower it to the bottom of the tank and remove the cork by pulling a string tied to it. Another slightly more elegant method of sampling is by using a glass tube of convenient length and considerable size, its lower end being drawn to a smaller diameter. The operator closes this tube at the top by his hand, thrusts it to the bottom of the tank and allows it to fill. When it is full he again closes the top, withdraws the tube and places the oil in a properly marked bottle to be taken to the testing laboratory.

If the oil, when tested, is found to be defective, it must be dried before the transformer suffers injury. Sometimes this is done by disconnecting the transformer, and emptying and filling with dry oil while the moist oil is taken to the central station to be dried and used again. More often, the drying apparatus, of which there are several styles on the

market, is taken to the transformer and connected to it. It then draws oil from the bottom of the tank and returns it at the top until all is fairly dry, thus avoiding an interruption of service.

When moisture is present in oil, it is always in a finely divided form like an emulsion and tends to settle to the bottom at a rate depending upon the size of the drops and the viscosity of the oil. This tendency to settle by gravity is opposed by the convection currents in the oil and by the attraction of the electrostatic field. If the particles are so very small that their rateof settling is considerably slower than the motion of the oil, only a small portion of them will separate out on the bottom while the rest will continue in suspension.

The seriousness of the danger due to moisture in suspension is increased by its action when under the influence of the electrostatic field. Since its specific inductive capacity is much greater than that of the oil, it is attracted to the points where the electrostatic field is most intense, or in general, to the places where the distance to ground or between terminals is shortest. This causes the oil at these points of greatest stress to be weaker than the remainder. The insulation at these points is usually reinforced by pressboard which can be wet by water in the same way as blotting paper though to a less extent. Since the surface-tension of water is greater than that of oil, it will displace the oil in any more or less porous material which it can wet. This may

easily be shown by placing a piece of oil soaked blotting paper in water. The oil collects in big drops which rise to the surface, leaving the blotting paper water soaked but without oil. In the same way, the moisture in oil which is retained at the points of greatest stress, after being drawn electrostatically to the insulating material, is retained by capillary attraction causing the gradual deterioration of the solid insulation.

Even if the oil is removed and dried as soon as it shows a marked decrease in strength, the solid insulating material is not improved by that means, but is only protected from further harm until the moisture begins to accumulate again in the oil. Neither can protection be secured by any system of intermittant drying of the oil unless this is done so often that no appreciable amount of moisture accumulates and the cost of this would be prohibitive. Such protection can be secured, however, by the use of a chemical dryer which absorbs the moisture as fast as it appears and so keeps the oil in a uniformally dry condition. By this means, there is no danger of breakdown by failure of the oil itself and no deterioration of the solid insulating material.

VII. CHEMICAL DRIERS.

The ideal way to guard against moisture in a transformer would be to absorb it chemically as fast as it appeared. To find a sufficiently powerful drier, of which there are manyin use by chemists, is not at all difficult, but as a rule, these are unsuitable for use in a transformer. Some of the driers are violent oxidizing agents and others form compounds with water which could react with the oil. With one or two exceptions, these have been rejected without trial. Below are considered the majority of those which have been tested at this laboratory.

In the preliminary trials, about a quart of new oil was placed in a bottle and shaken well with water. Then the drying material was added and the bottle set aside. Since this test was at room temperature, the action of the driers was stronger and the tendency to other chemical action weaker than it would be under operating conditions at a higher temperature, and so the conditions were not severe. Those driers which passed this test were next tried at a higher temperature in an oven. The final trial was made in a transformer case with a larger amount of oil, lamps for keeping the oil hot at 60 C, and with the drier contained in cloth bags exactly as it would be in service. Below the various driers are discussed and compared.

Sponges and blotting paper: It has been noted by other experimenters that water will displace oil in any porous material which it can wet. If a drop of water is placed on a sponge or piece of blotting paper in oil, it will quickly

be soaked up, suggesting that these materials might either of them be used for drying oil. Indeed, one manufacturer is placing on the market an oil drier in which the process is simply to pump the oil through blotting paper. Test shows that the action is too feeble to be effective when the oil simply circulates past the blotting paper and is not forced through it. If the drop merely passes along the surface of the paper, it will not be absorbed. While the paper and the sponge took up some moisture in the tests, they did not leave the oil perfectly dry and are therefore unsuitable for use

Quicklime or CaO is used by another manufacturer in oil drying apparatus, the oil being pumped through the lime and afterwards filtered. It takes up water, forming $Ca(OH)_2$, a compound that is stable to a very high temperature. The oil containing it gives a neutral reaction. The only objection to theuse of lime is the mechanical one that the pieces are not strong and the dust which breaks away will float for some time in the oil.

Anhydrous copper sulphate is sometimes used for detecting moisture in oil because of its color change as it takes up water Since it is a very fine grayish powder, it is unsuitable for use directly in the oil, so the scheme was tried of using it in blotting paper, hoping that the fibers of the paper would hold the copper sulphate in place. Despite this precaution, there was some muddiness of the oil due to the particles that escaped and the drying action was rather feeble, even at room temperature. While ordinarily copper sulphate can keep five molecules as water of crystallization, at 78 C it can

retain only one, so its drying action becomes extremely poor, almost vanishes, even at temperatures to which it would be subjected in a transformer. Then too, it would be a source of danger in a transformer because of its corrosive action due to the ease with copper replaces other metals.

Sodium sulphate, Na_2SO_4, is even poorer than copper sulphate for, although the pieces are harder originally, they seem to disintegrate under the action of moisture. The pieces so formed are feathery and float easily in the oil. It loses its water of crystallization at 32 C making it entirely unsuitable for drying the oil of transformers in service.

Calcium chloride, $CaCl_2$, has some excellent points in its favor and has been considerably used at this laboratory. Like the other chemicals named above with the exception of quicklime, it takes up moisture as water of crystallization and therefore gives a perfectly neutral reaction. Since it retains the water to above 100 C, it is a strong drier even at the highest temperature to which it would be subjected. The objection again is mechanical for, as moisture is taken up, especially at the higher temperatures, minute particles separate out and float in the oil. A portion of this material is so fine that it will pass a coarse filter and it gives the oil an opaque muddy look. The plan was also tried of dissolving the calcium chloride in alcohol, allowing this to impregnate blotting paper and then driving off the alcohol with heat, thus leaving the calcium chloride in the blotting

paper. The paper assists in retaining the fine material in place and gives fairly satisfactory results.

Metallic sodium is a very active drier for it combines with water forming a strong base, NaOH, and setting hydrogen free. It may be easily prepared for use by warming it under oil to 95 C, when it will melt and may be separated into globules which show little tendency to recombine. The sodium hydrate formed is chiefly objectionable because it sloughs off and some of the particles float in the oil.

Metallic calcium shows some advantages over both metallic sodium and quicklime. Its density is considerably greater than that of the oil being about 1.7 while sodium is 0.98 and therefore only slightly heavier than oil. The compound $Ca(OH)_2$, which it forms with water, is very little soluble and clings closely to the metal. If a lump of calcium is placed in moist oil, it forms a scale over the outside and, after that, will not be affected by water. While this seems at first like a disadvantage, it really is the feature that makes the use of calcium practicable, for the scale so formed does not go free in the oil as with most of the other driers. The metal may be turned in a lathe and turnings prepared for use in this way. By cutting these of the proper size, very little of the material will go to waste. Unlike sodium, calcium may be handled freely in air and does not constitute a fire hazard. The metallic shavings, when placed in a light cloth bag and hung near the bottom of a transformer will remove all moisture floating in the oil and prevent its accumulation so long as there is free

metal exposed. The metal may be removed and fresh supplied at intervals of perhaps six months or even longer. While the present price of calcium is high, something over one dollar a pound in small lots, this is because there has been no demand for the metal and not because the processes of manufacture are difficult. It can probably be made as cheaply as sodium.

VIII CONCLUSIONS.

It is interesting and suggestive to notice that practically all the peculiarities of the electrostatic disruption of dry oil may be explained by considering that oil is not a perfectly homogeneous liquid but one in which there are present multitudes of minute gas bubbles that affect breakdown by their action under stress. While some of these phenomena may be explained equally well on the basis of ionization, yet sometimes this would produce quite the opposite effect. For instance, ionization of the oil would require it to break down easier, if stressed for some time, yet the effect is quite the reverse, and dry oil will break down easier if the voltage is brought up quickly than if increased very slowly.

The photographs are instructive in indicating that the arc in oil, like that in air, is preceded by a static spark. The arc also shows the same tendency to drive through on a small, highly conducting path, in oil as in air.

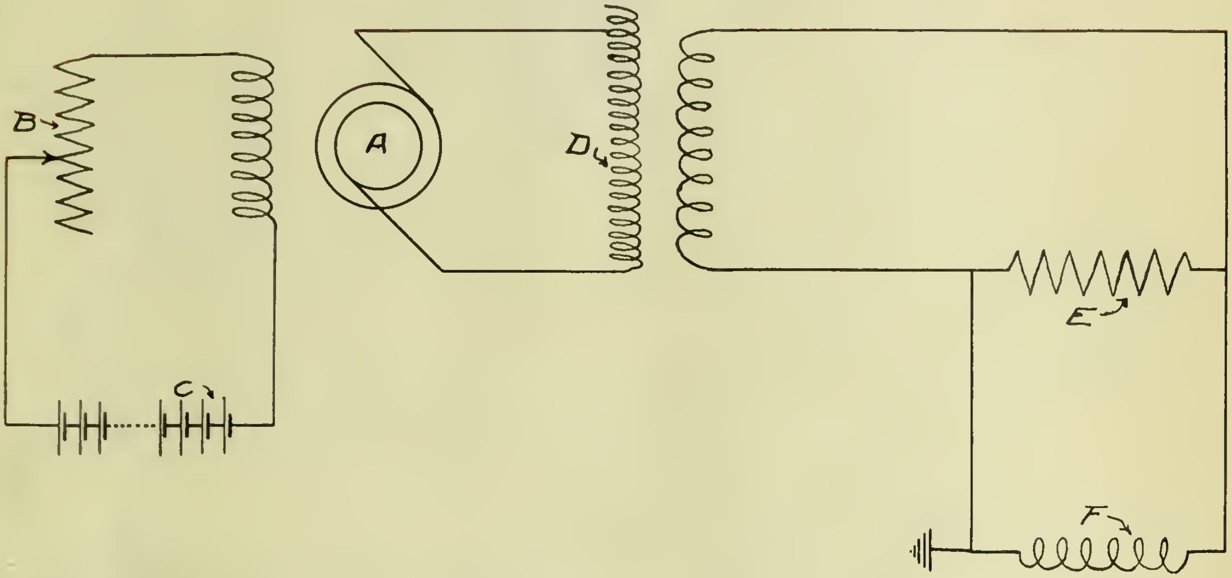
The suggestion of the part that bubbles play in producing disruption leads almost directly to a method of test that gives accurate results.

The tests of chemical driers indicate that metallic calcium may in future, be used to guard transformers in sevice against moisture.

IX.

Diagram of Electrical Connections.

FIG 1.



A. Smooth core alternator 60~ 500 volt.

B. Alternator field rheostat.

C. Storage battery 60 cells.

D. Variable ratio transformers (not in
circuit for voltages above 50 K.V.)

E. Rheostat to preserve wave form.

F. High potential transformer

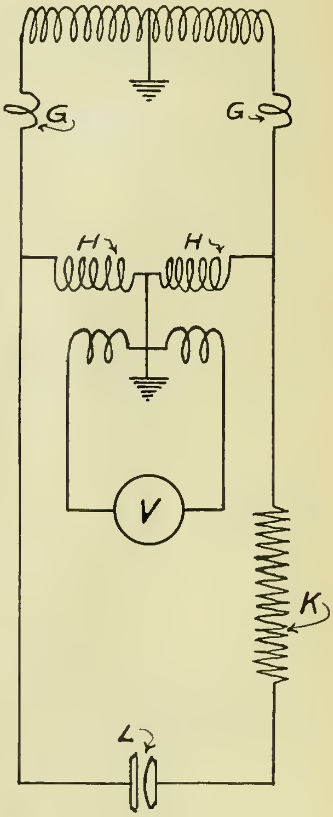
G. Reactance coils to protect end turns.

H. Instrument transformer 33,000–110 volts
(disconnected for voltages above 66 K.V.)

V. Voltmeter.

K. Carborundum resistance.

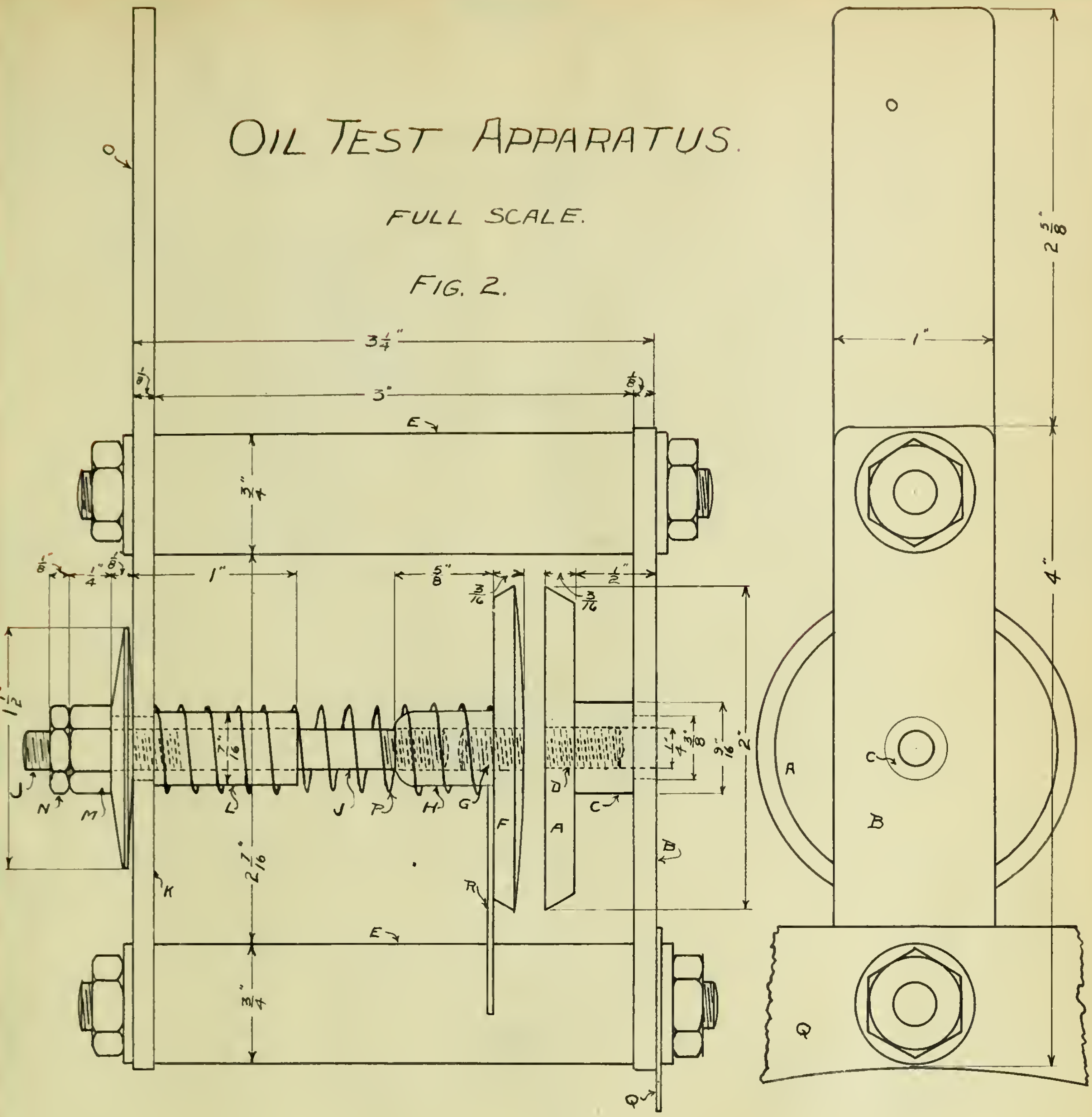
L. Test apparatus.



OIL TEST APPARATUS.

FULL SCALE.

FIG. 2.



A. Plane electrode.

B. Brass side ⅛ × 1" section.

C. Turned block soldered into B.

D. Screw soldered into A.

E. Rubber rods threaded on ends for nuts.

F. Spherical electrode radius of curvature.

G. Screw soldered into F.

H. Turned block for holding electrode.

J. Rod carrying electrode and micrometer.

K. Brass side ⅛ × 1" section.

L. Sleeve soldered into K.

M. Micrometer nut.

N. Lock nut for M.

O. Extension of side for holding apparatus when changing papers

P. Steel coil spring.

Q. Brass piece 4" long acting as two legs

R. Strip to keep electrode F from turning.

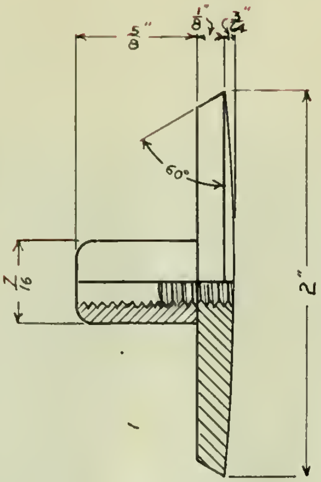


Fig. 3.

Regular terminal used on test apparatus as shown in Fig. 2.

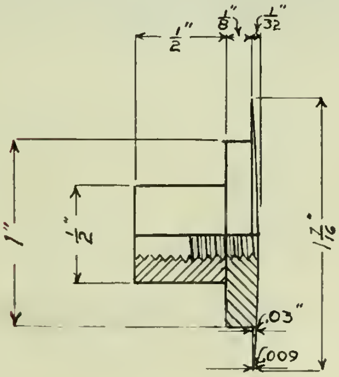


Fig. 4.

Special terminal showing thin edge.

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X.

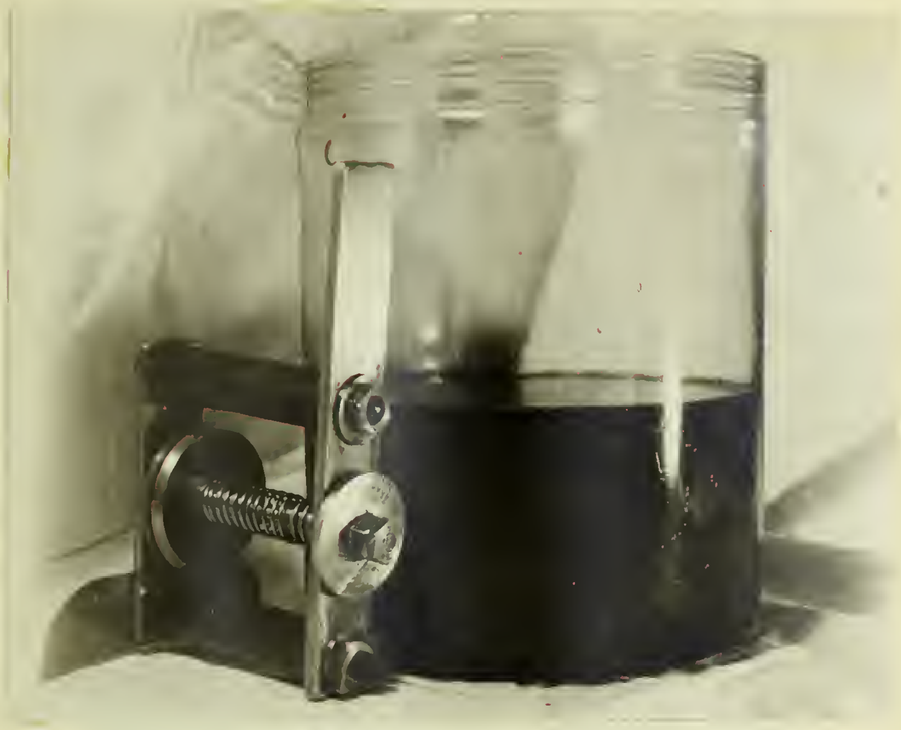

Fig. 5.

TEST APPARATUS WITH JAR AND OIL.

For use with oil soaked blotting paper.

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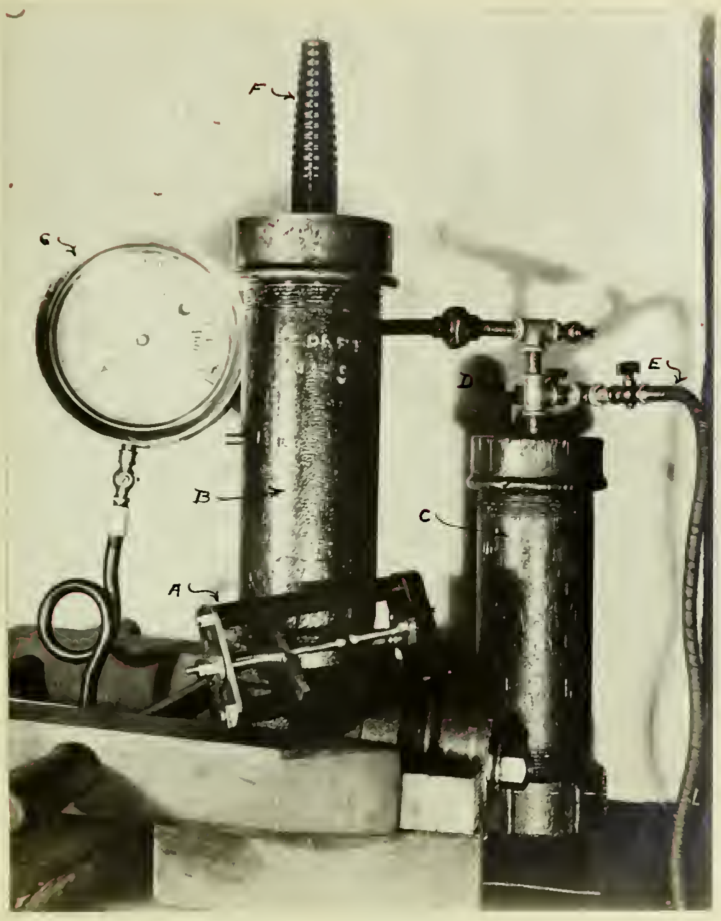

Fig. 6.

APPARATUS FOR TESTING OIL UNDER PRESSURE.

A	Test apparatus.
B	Oil chamber.
C	Air chamber.
D	Pressure connection.
E	Vacuum connection.
F	Insulator.
G	Gage.

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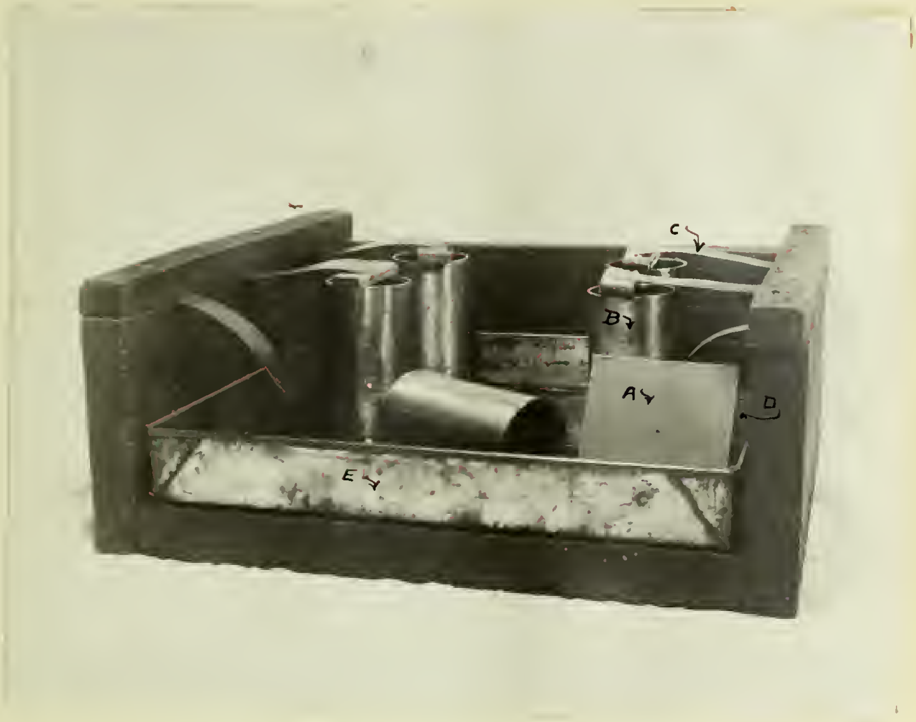

Fig. 7.

FILTRATION APPARATUS FOR MOISTURE TESTS.

A A square of the blotting paper.

B Brass tube in which sample is placed.

C Springs for holding tubes in place.

D Screen wire under tubes and paper.

E Pan for retaining oil.

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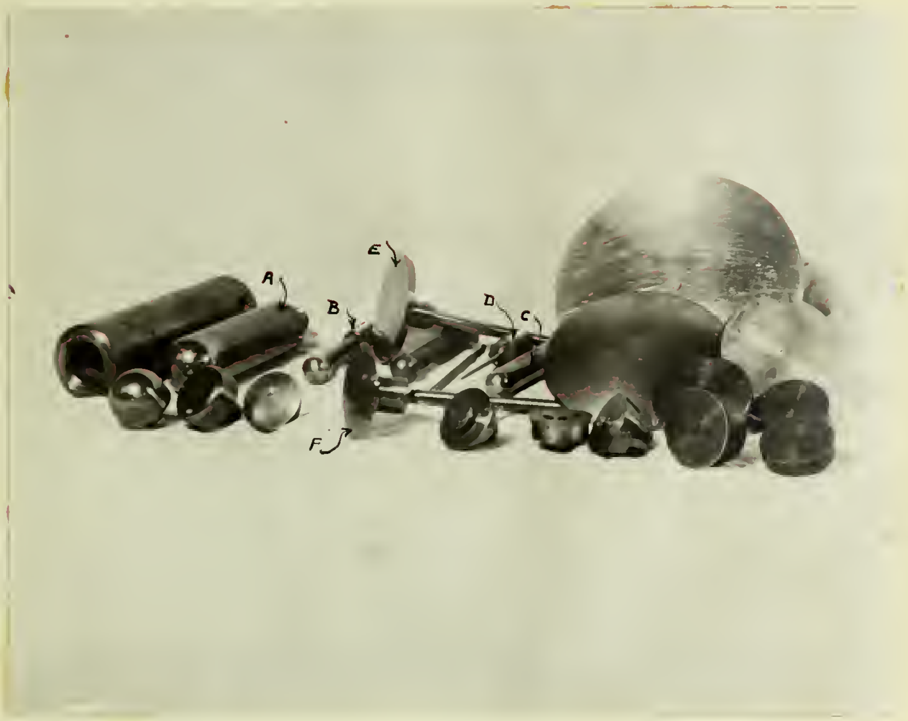

Fig. 8.

A FEW ELECTRODES - One of a kind.

A 1 inch round nosed.

B 1/2 inch, spherical.

C 1/2 inch, round nosed.

D 1/16 inch, round nosed.

F Electrode for blotting paper - ordinary construction.

F Electrode for blotting paper - thin edge.

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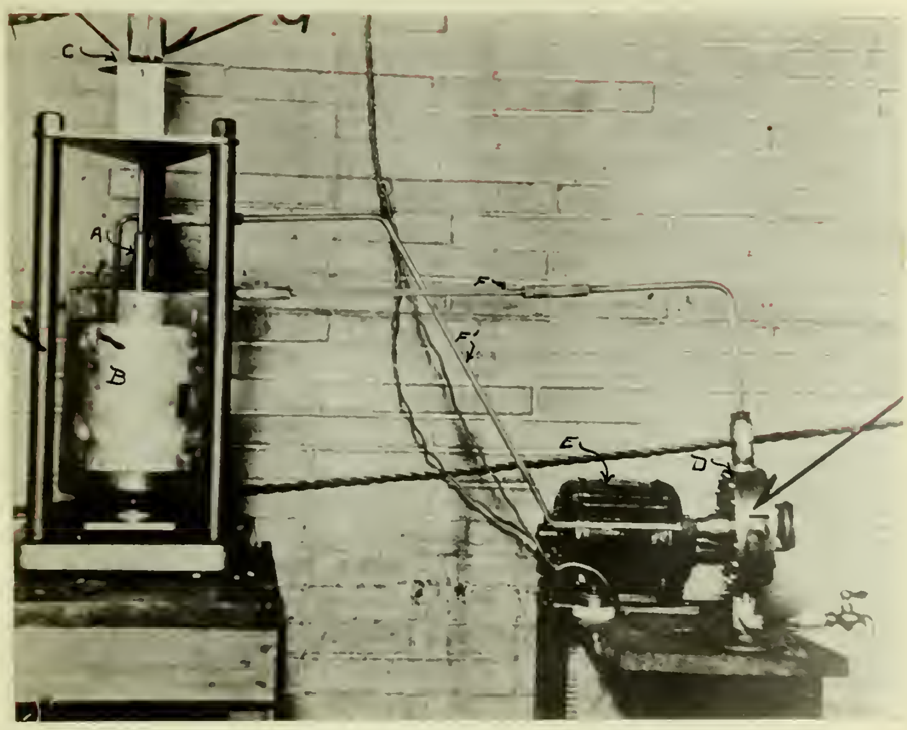

Fig.79.

APPARATUS FOR TESTING OIL WHEN CIRCULATING.

A	Upper terminal.
B	Containing jar coated with tinfoil to produce a uniform field.
C	Micrometer.
D	Centrifugal pump.
E	Motor for driving same.
FF'	Glass tubes for oil to pass through.

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XI

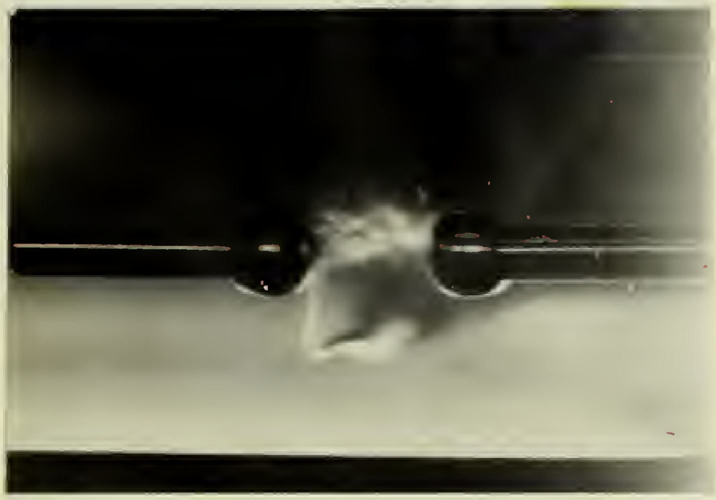

Fig. 10.

THE ARC IN OIL-NEW KEROSENE.

Electrode distance 0.5 inches.

Arc started by bubble from the tube shown at left.

Power limited by resistance, both in primary and secondary.

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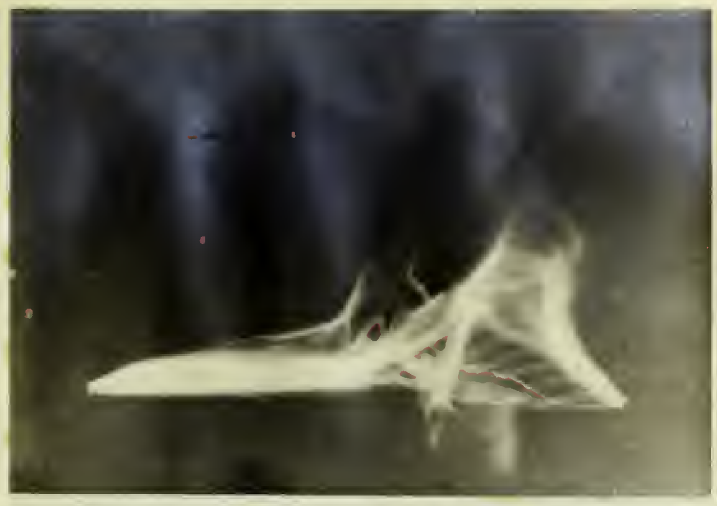

Fig. 11.

THE ARC IN AIR.

Spark gap, 8.0 inches.

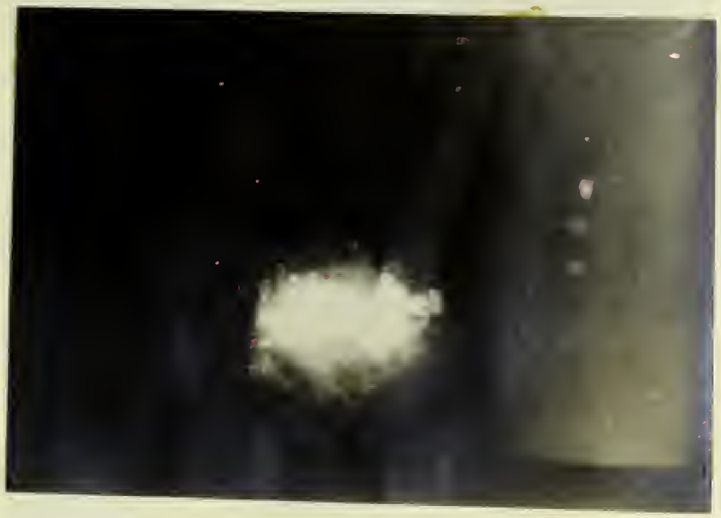

Fig. 12.

THE ARC IN OIL.

Spark gap, 0.25 inches.

Current limited to less than 0.5 ampere by carborundum resistance in series with the gap.

Note the static spark in each case.

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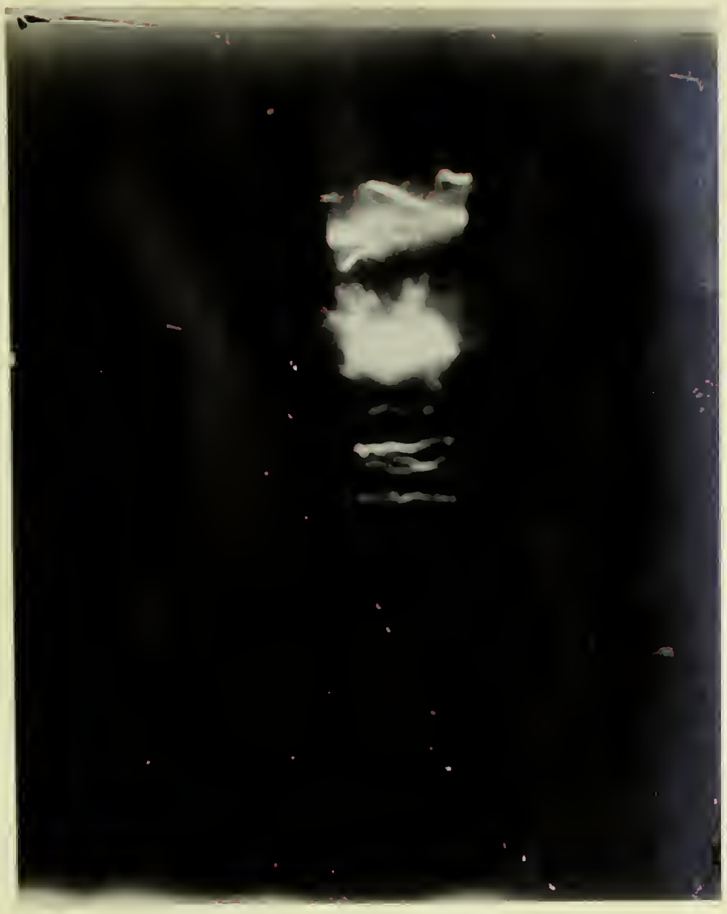

Fig. 13.

THE ARC IN OIL.

Formed across a horn gap.

Minimum gap 0.25 inches.

Power limited to less than 1 ampere by carborundum resistance.

Note the preliminary discharges (B.D.S.I.)

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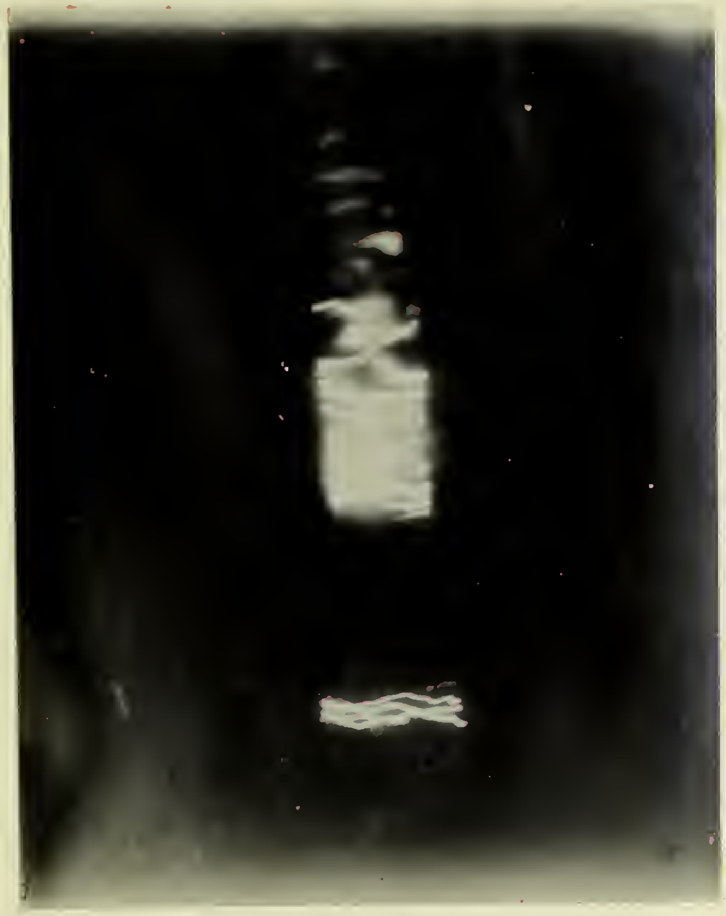

Fig. 14.

THE ARC IN OIL.

Same as Fig. 13, except that the power is more limited.

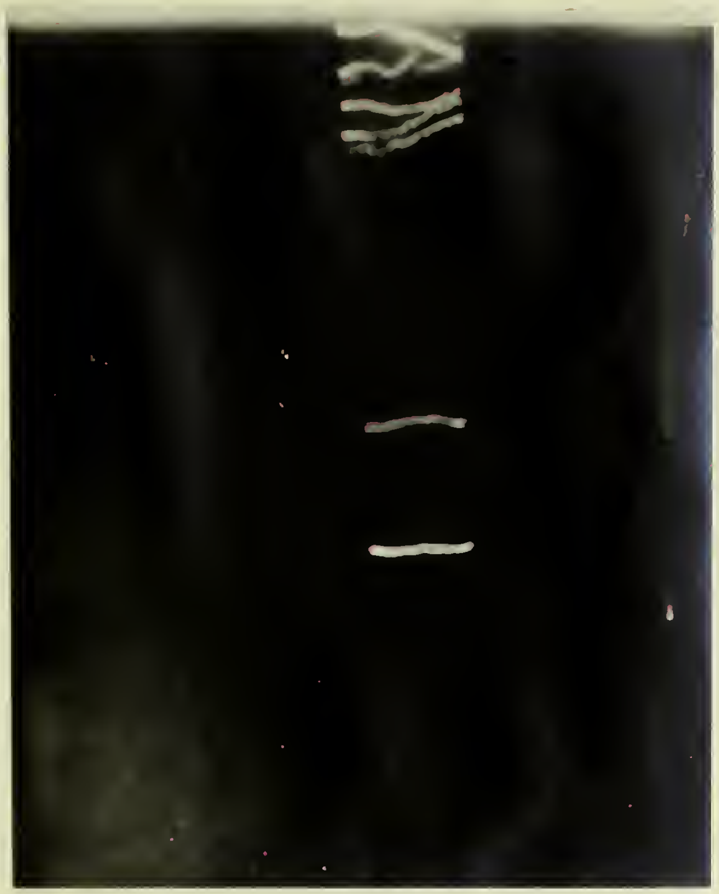

Fig. 15.

THE ARC IN OIL.

Same as Figs. 13 and 14, except that the power is still more limited.

Current less than 0.07 amperes.

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XII.

METHODS OF PREPARING PAPER - A COMPARISON.

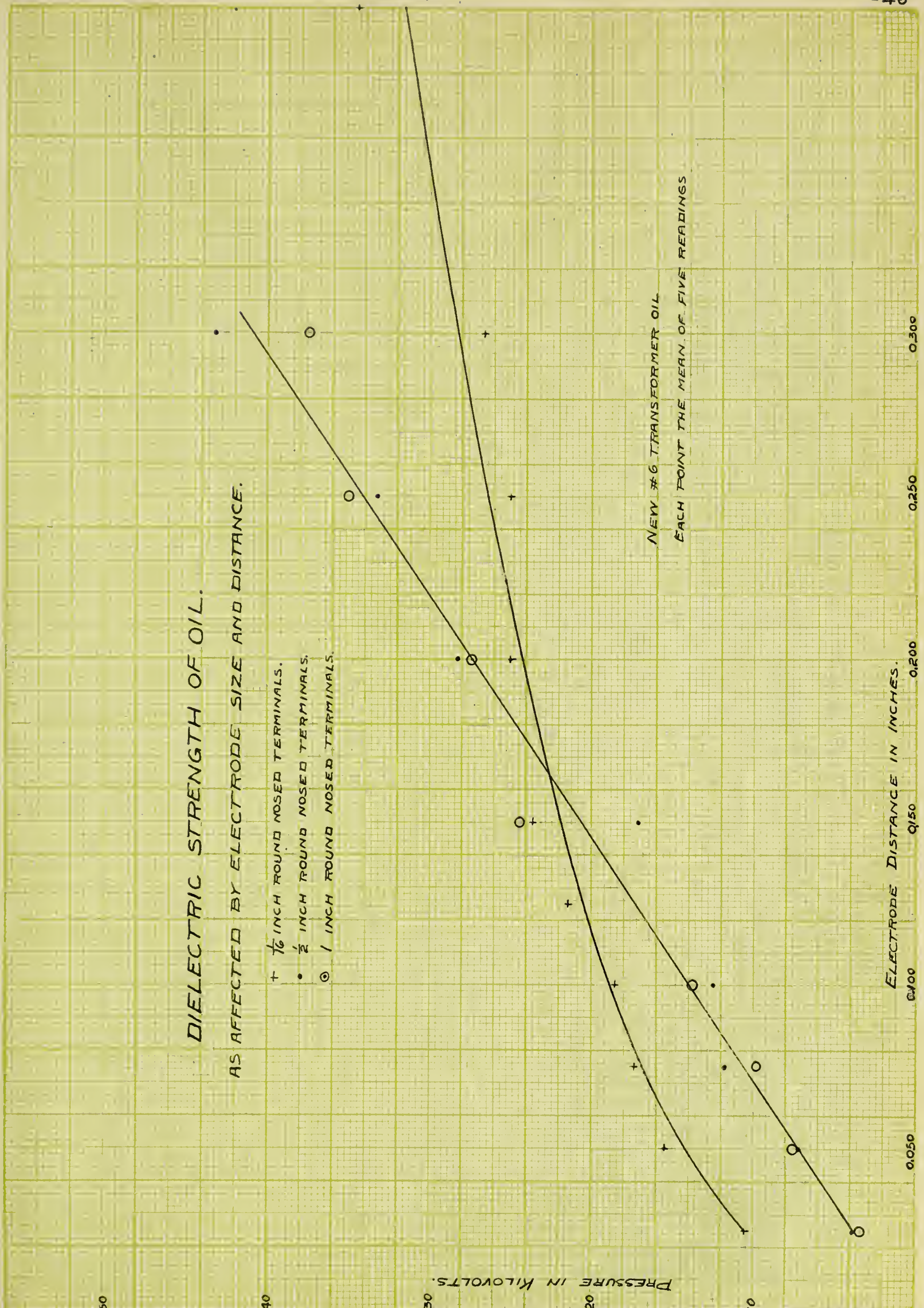
Showing little advantage of vacuum treatment except for time economy.

A. Papers dried in an oven, then placed in a dish edgewise the pieces separated by wires. Dish filled slowly with oil.

B. Papers dried in a vacuum with gentle warming, then placed edgewise in a dish and oil allowed to enter slowly in vacuum.

A. Volts	Discharge dist. from center.		B. Volts	Discharge dist. from center.
18900.	0.5 radius.		20100.	0.8 radius.
19200.	.6		18600.	.8
18900.	.6		19200.	.9
21000.	.7		18900.	.8
20400.	.9		18900.	.8
20700.	.7		18900.	.7
19500.	.6		18000.	.8
19200.	.3		17700.	.5
19800.	.8		20100.	.9
18300.	.3		18900.	.8
19590.	0.61	Mean	18930.	0.78
	7.2%	Maximum Deviation		6.5%

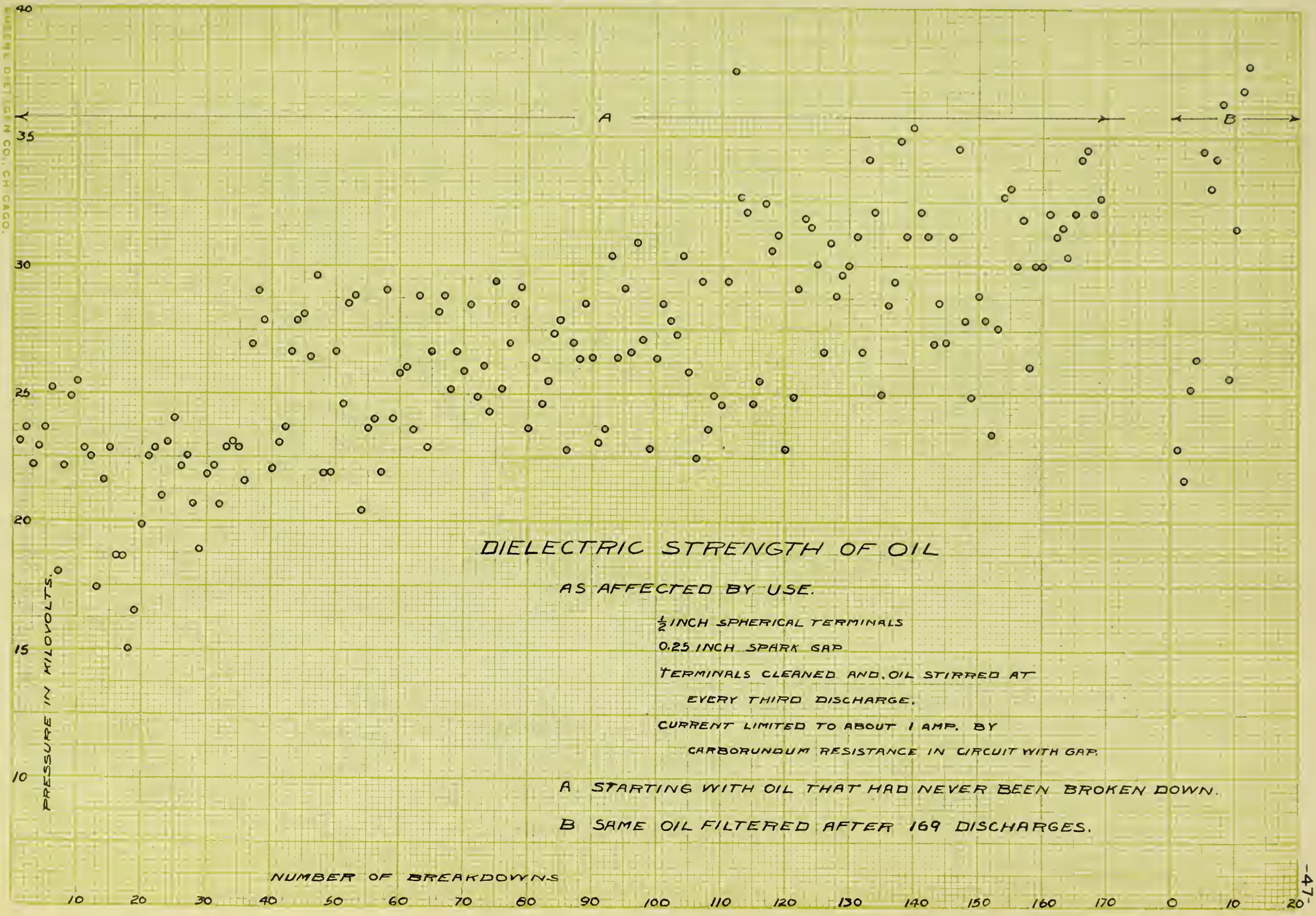
XIII.



DIELECTRIC STRENGTH OF OIL.

AS AFFECTED BY ELECTRODE SIZE AND DISTANCE.

EMPIRE DIETZGEN CO. CHICAGO



DIELECTRIC STRENGTH OF OIL

AS AFFECTED BY USE.

$\frac{1}{2}$ INCH SPHERICAL TERMINALS

0.25 INCH SPARK GAP

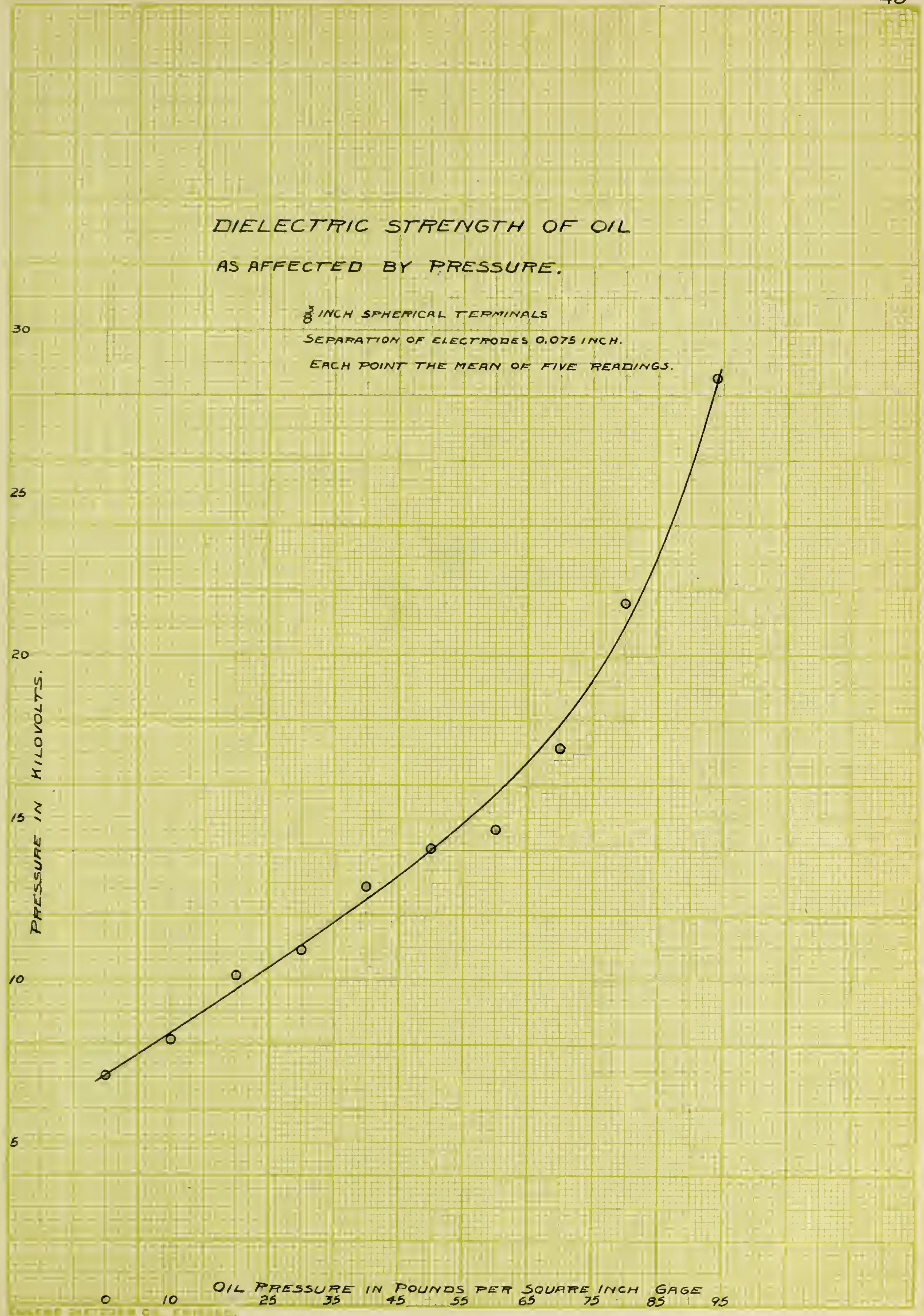
TERMINALS CLEANED AND OIL STIRRED AT EVERY THIRD DISCHARGE.

CURRENT LIMITED TO ABOUT 1 AMP. BY CARBORUNDUM RESISTANCE IN CIRCUIT WITH GAP.

A STARTING WITH OIL THAT HAD NEVER BEEN BROKEN DOWN.

B SAME OIL FILTERED AFTER 169 DISCHARGES.

EUGENE DIETZGEN CO., CHICAGO.



DIELECTRIC STRENGTH OF OIL

AS AFFECTED BY PRESSURE.

$\frac{3}{8}$ INCH SPHERICAL TERMINALS

SEPARATION OF ELECTRODES 0.075 INCH.

EACH POINT THE MEAN OF FIVE READINGS.

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